THE EVOLVABLE MARS CAMPAIGN

NAC Research Sub Committee
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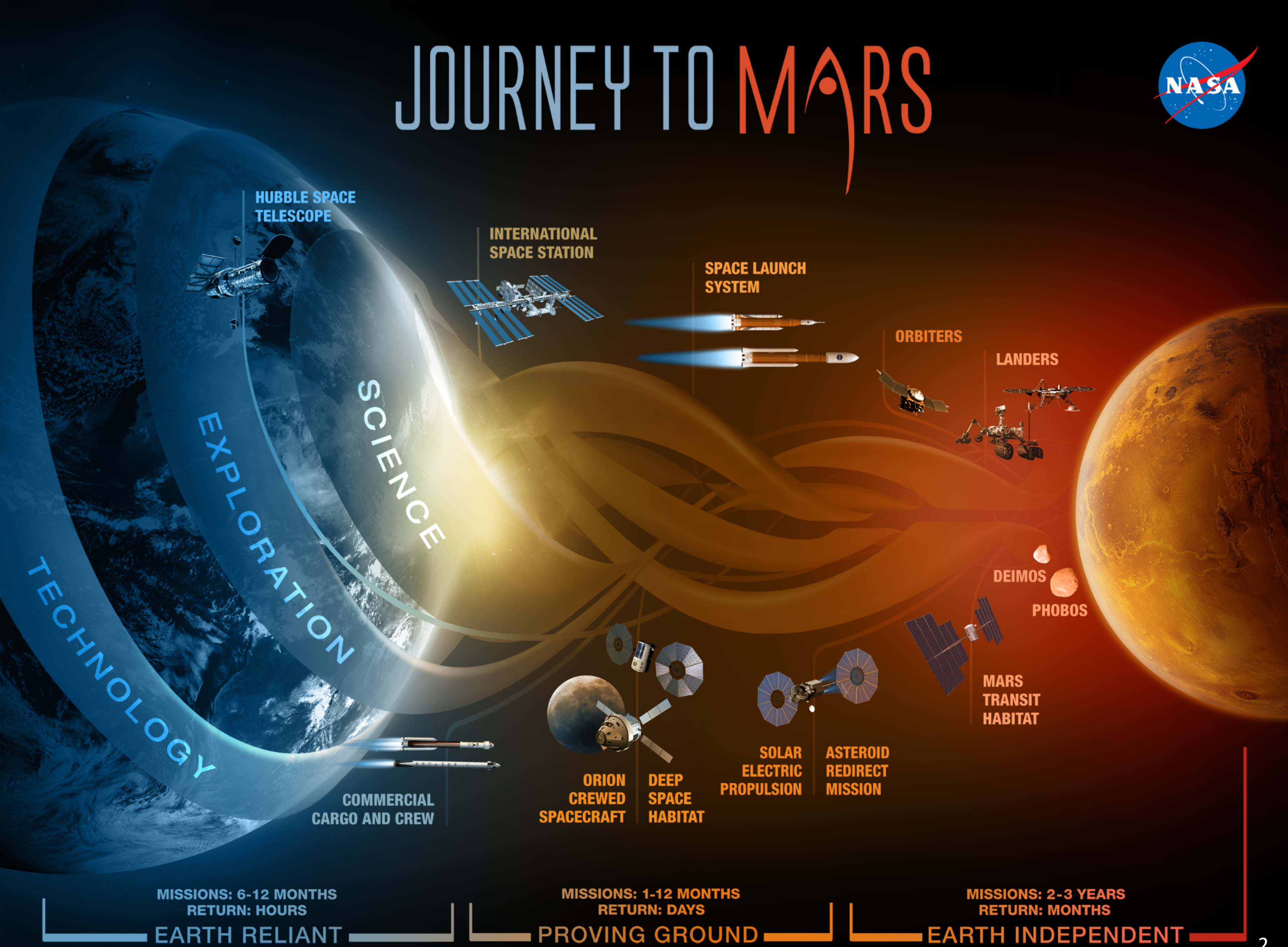
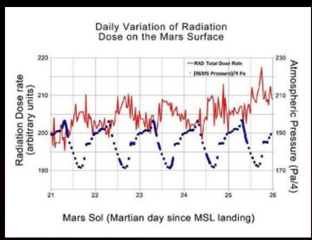

JOURNEY TO MARS
NASA
HUBBLE SPACE TELESCOPE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
DEIMOS
PHOBOS
MARS TRANSIT HABITAT
COMMERCIAL CARGO AND CREW
ORION CREWED SPACECRAFT
DEEP SPACE HABITAT
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT
MISSIONS: 1-12 MONTHS
RETURN: DAYS
PROVING GROUND
MISSIONS: 2-3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

Human Exploration of Mars Is Hard

Common Capability Needs Identified from Multiple Studies

800-1,100 Days

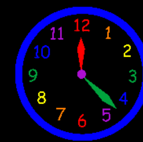
Total time crew is away from Earth – for orbit missions all in Micro-g and Radiation



Long Surface Stay

500 Days

44 min



Maximum two-way communication time delay – Autonomous Operations

130 t

Heavy-Lift Mass

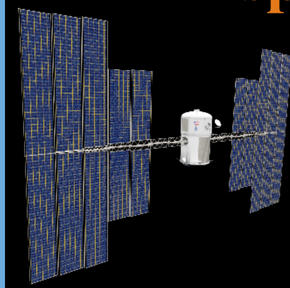
Multiple

Launches per mission

11.2 km/s

Earth Entry Speed

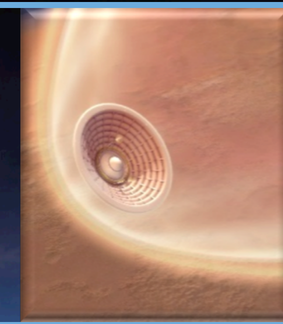
Reliable In-Space Transportation



Total continuous transportation power

20-30 t

Ability to land large payloads



Surface Operations

Dust Toxicity and Long Range Exploration

20 t

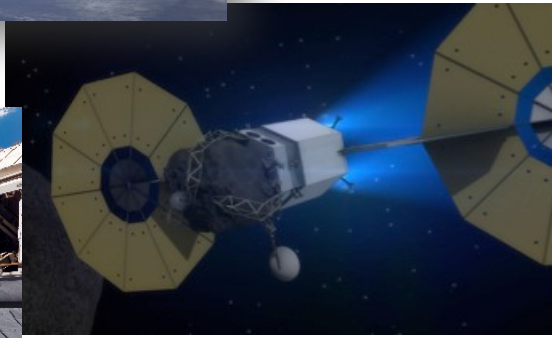
Oxygen produced for ascent to orbit - ISRU

Mars is Achievable If We Take the Long View

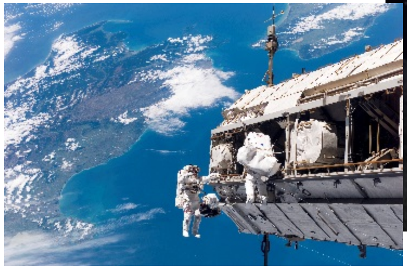
- **Space Launch System**
  - Engines
  - Stages (including EUS)
  - Boosters
- **Orion Crew Vehicle**
- **Ground System Development and Operations**

- **Commercial Crew & Cargo Vehicles**

- **Asteroid Redirect Mission**
  - Capture mechanism
  - Solar electric propulsion
  - Spacecraft bus and solar arrays



- **ISS Experiments & Research**



HEOMD has more space systems development ongoing today than at any time since Apollo!

What We've Learned Thus Far and Still Need to Learn

Orbital Environment and Operations

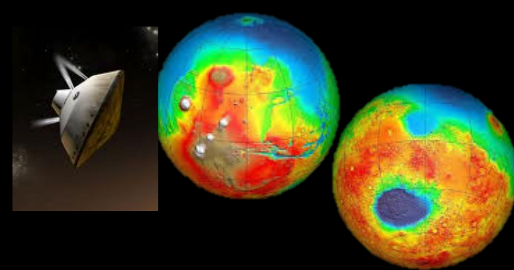
Learned:

- Deep space navigation
- Orbit transfer near low-gravity bodies
- Gravity assist
- Aero-braking
- Gravitational potential
- Mars's moons' characteristics
- ISRU potential

To Learn:

- Return flight from Mars to Earth
- Autonomous rendezvous and docking
- ISRU feasibility
- Resource characterization of Mars's moons
- High-power SEP

Capture, EDL, and Ascent at Mars



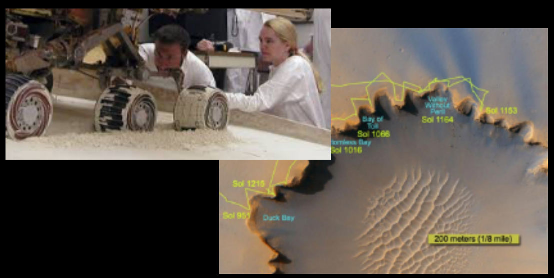
Learned:

- Spatial/temporal temperature variability
- Density and composition variability
- Storm structure, duration, and intensity
- 1 mT payload
- ~10 km accuracy

To Learn:

- Ascent from Mars
- Large-mass EDL
- Precision EDL
- Aero-capture
- Site topography and roughness
- Long-term atmospheric variability

Surface Operations at Mars



Learned:

- Water once flowed and was stable
- Global topography: elevation and boulder distributions
- Remnant magnetic field
- Dust impacts on solar power/ mechanisms
- Radiation dose
- Global resource distribution
- Relay strategies, operations cadence

To Learn:

- Landing site resource survey
- Dust effects on human health, suits, and seals
- Rad/ECLSS in Mars environment
- Power sufficient for ISRU
- Surface navigation

Evolvable Mars Campaign

EMC Goal: Define a pioneering strategy and operational capabilities that can extend and sustain human presence in the solar system including a human journey to explore the Mars system starting in the mid-2030s.

- **Identify a plan that:**
  - Expands human presence into the solar system to advance exploration, science, innovation, benefits to humanity, and international collaboration.
  - Provides different future scenario options for a range of capability needs to be used as guidelines for near term activities and investments
    - In accordance with key strategic principles
    - Takes advantage of capability advancements
    - Leverages new scientific findings
    - Flexible to policy changes
  - Identifies linkages to and leverage current investments in ISS, SLS, Orion, ARM, short-duration habitation, technology development investments, science activities
  - Emphasizes prepositioning and reuse/repurposing of systems when it makes sense
    - Use location(s) in cis-lunar space for aggregation and refurbishment of systems

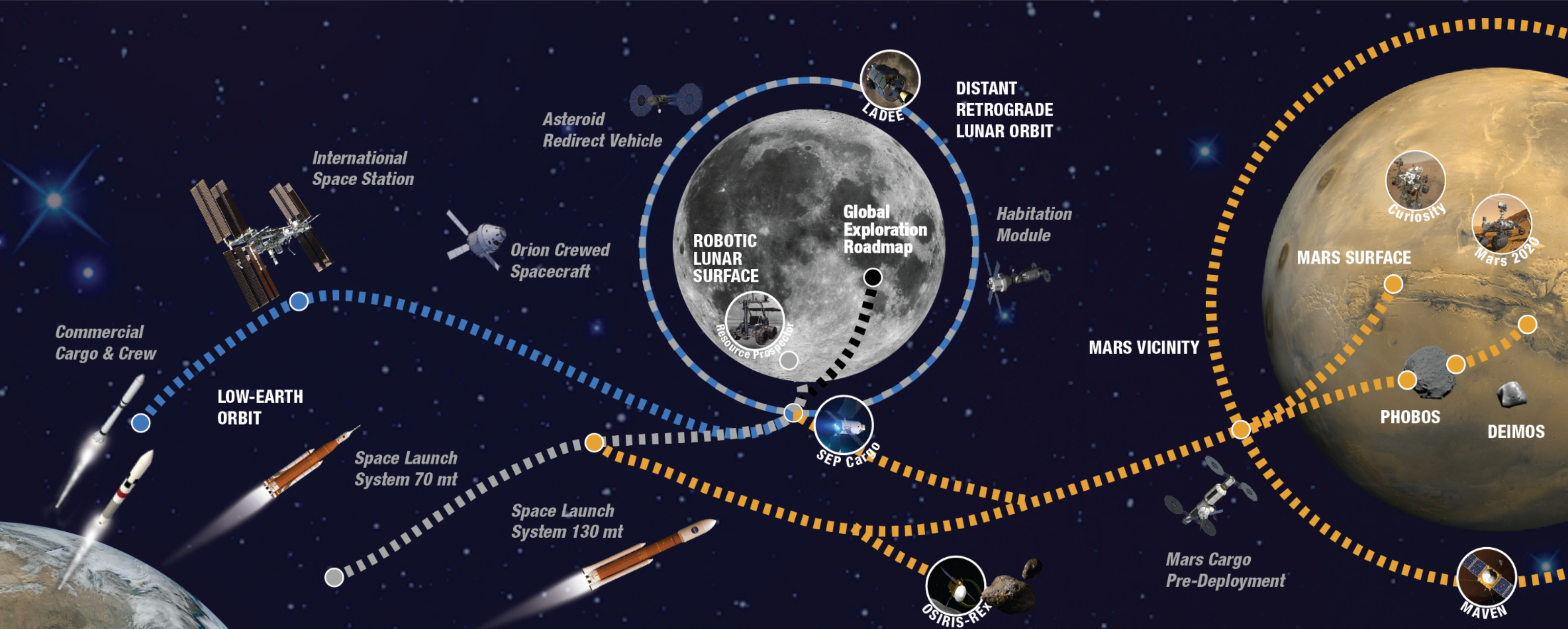
Internal analysis team members:
- ARC, GRC, GSFC, HQ, JPL, JSC, KSC, LaRC and MSFC
- HEOMD, SMD, STMD, OCS and OCT

External inputs from:
International partners, industry, academia, SKG analysis groups

EVOLVABLE MARS CAMPAIGN

A Pioneering Approach to Exploration

EARTH RELIANT | PROVING GROUND | EARTH INDEPENDENT



THE TRADE SPACE

Across the Board | Solar Electric Propulsion • In-Situ Resource Utilization (ISRU) • Robotic Precursors • Human/Robotic Interactions • Partnership Coordination • Exploration and Science Activities

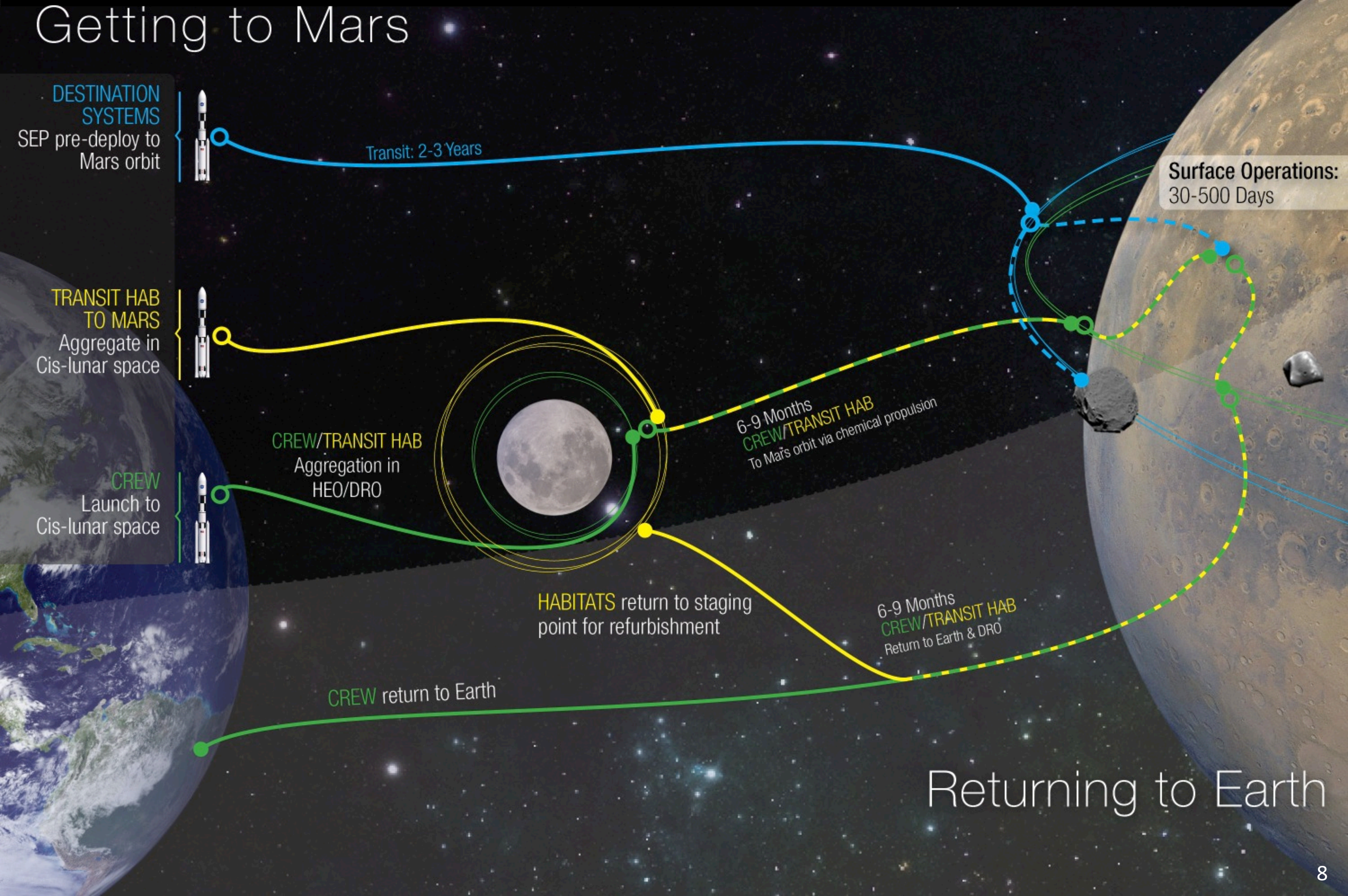
Cis-lunar Trades

- Deep-space testing and autonomous operations
- Extensibility to Mars
- Mars system staging/refurbishment point and trajectory analyses

Mars Vicinity Trades

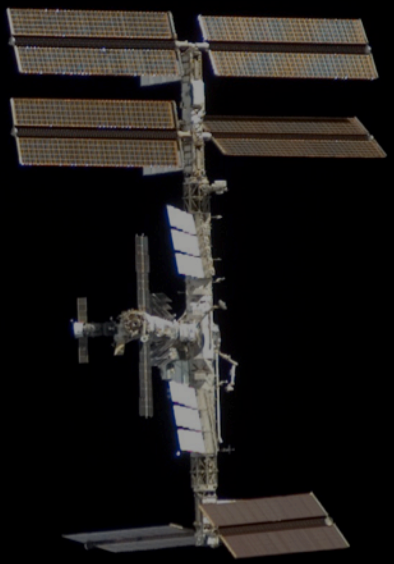
- Split versus monolithic habitat
- Cargo pre-deployment
- Mars Phobos/Deimos activities
- Entry descent and landing concepts
- Transportation technologies/trajectory analyses

Split Mission Concept



EARTH RELIANT

NEAR-TERM OBJECTIVES



DEVELOP AND VALIDATE EXPLORATION CAPABILITIES IN AN IN-SPACE ENVIRONMENT

- Long duration, deep space habitation systems
- Next generation space suit
- Autonomous operations
- Communications with increased delay
- Human and robotic mission operations
- Operations with reduced logistics capability
- Integrated exploration hardware testing

LONG-DURATION HUMAN HEALTH EVALUATION

- Evaluate mitigation techniques for crew health and performance in micro-g space environment
- Acclimation from zero-g to low-g

COMMERCIAL CREW TRANSPORTATION

- Acquire routine U.S. crew transportation to LEO

Transition from ISS to Cislunar Space: Framework

Today

Ends with testing, research and demos complete*

Phase 0: Exploration Systems ***Testing on ISS***

Asteroid Retrieval Crewed Mission Marks Move from Phase 1 to Phase 2

Phase 1: ***Cislunar Flight Testing*** of Exploration Systems

Ends with one year crewed Mars-class shakedown cruise

Phase 2: ***Cislunar Validation*** of Exploration Capability

Mid-2020s

2030

*There are several other considerations for ISS end-of-life

PROVING GROUND OBJECTIVES

Enabling Human Missions to Mars

TRANSPORTATION

- **Heavy Launch Capability**: beyond low-Earth orbit launch capabilities for crew, co-manifested payloads, large cargo
- **Crew**: transport at least four crew to cislunar space
- **In-Space Propulsion**: send crew and cargo on Mars-class mission durations and distances

WORKING IN SPACE

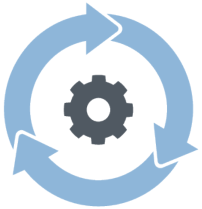
- **ISRU**: Understand the nature and distribution of volatiles and extraction techniques and decide on their potential use in human exploration architecture.
- **Deep-space operations capabilities**: EVA, Staging, Logistics, Human-robotic integration, Autonomous operations
- **Science**: enable science community objectives

STAYING HEALTHY

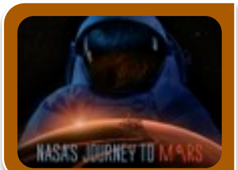
- **Deep-Space Habitation**: beyond low-Earth orbit habitation systems sufficient to support at least four crew on Mars-class mission durations and dormancy
- **Crew Health**: Validate crew health, performance and mitigation protocols for Mars-class missions

Evolvable Mars Campaign – Strategy Development

Updated Information



- System performance
- Reliability
- Destination information
- Cost, schedule, etc.



JOURNEY TO MARS
Human Mars Missions are challenging. Everything we are doing now focuses on sending the first human pioneers to the Martian system.

TRADE STUDIES
Architectural trade analyses defining capabilities for human Mars missions.

Major Study Questions (A-N) • System Maturation Team Capability information • Existing Program Data

CAPABILITIES REQUIRED
Earth to space transportation • Habitation • In-space transportation • Destination systems • Technology investment strategies

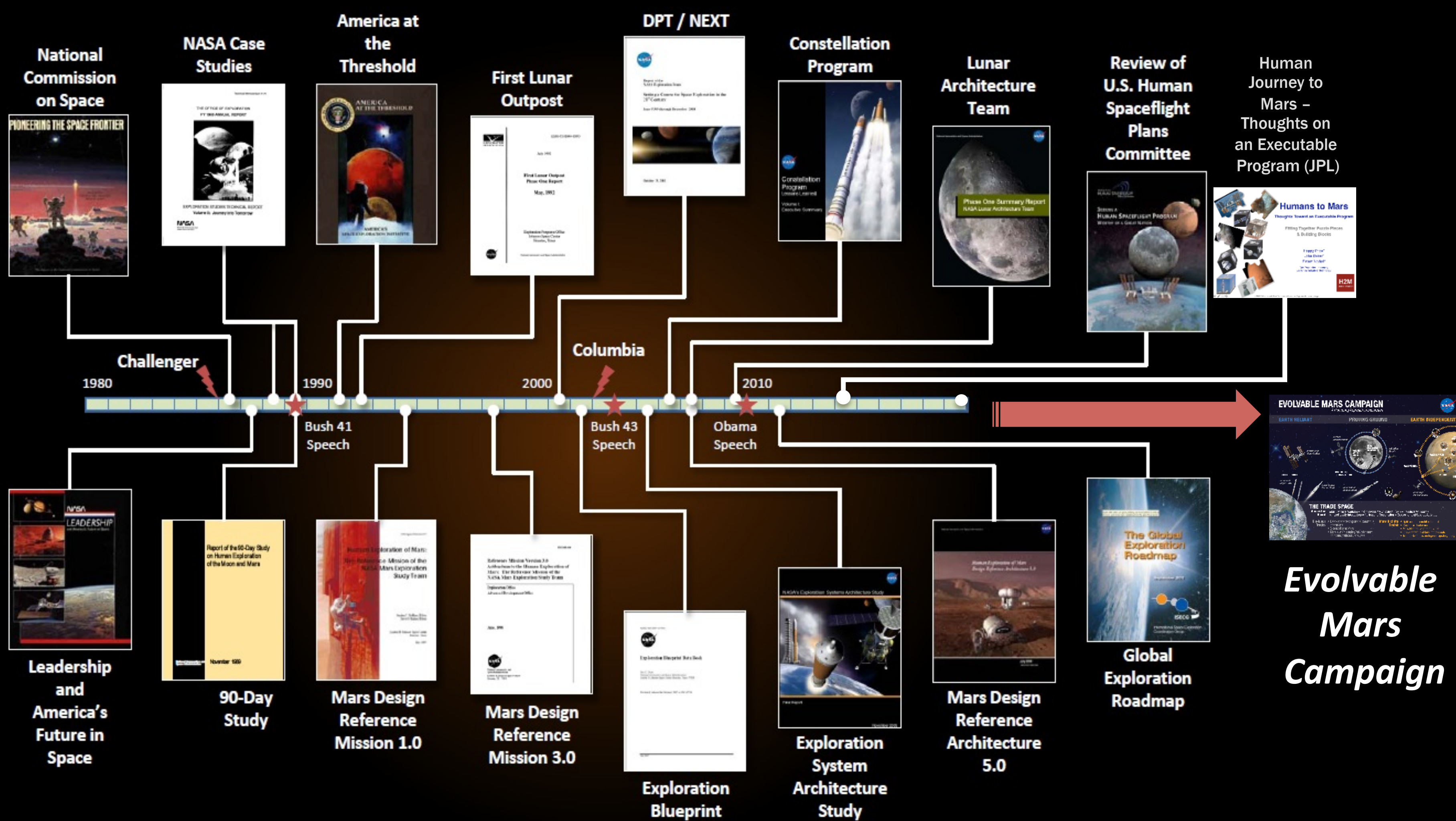
COMPLEXITIES AND CHALLENGES
Risk Areas • Programmatic Dependencies

FLIGHT TEST OBJECTIVES
Earth Reliant • Proving Ground • Earth Independent

IMPLEMENTATION STRATEGIES
Mission Sequence • Partnerships

PROGRAMS AND PROJECTS
International Space Station • SLS and Orion • Asteroid Redirect Mission • Habitation

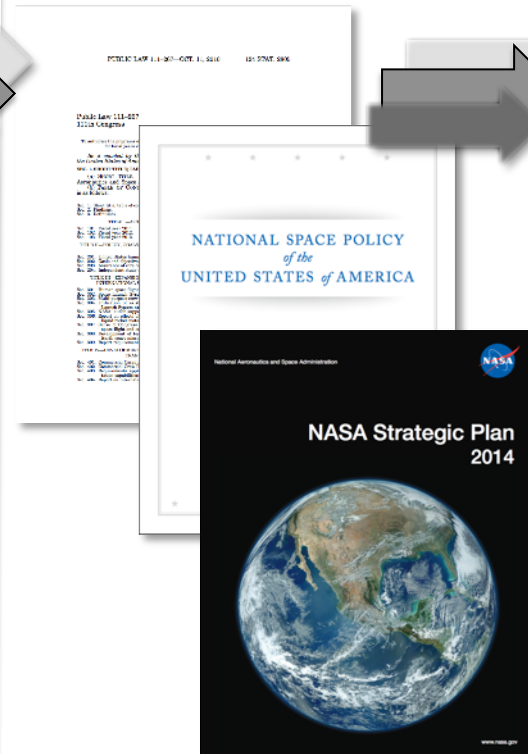
A Brief History of Beyond-LEO Spaceflight Architecture Development



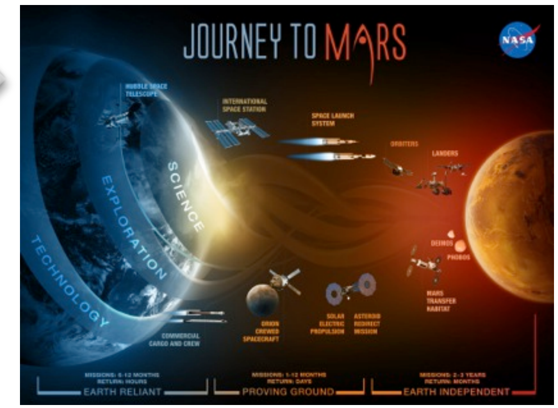
Evolvable Mars Campaign – Study Activity

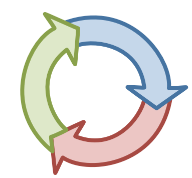
Body of Previous Architectures, Design Reference Missions, Emerging Studies and New Discoveries	2010 Authorization Act, National Space Policy, NASA Strategic Plan	Evolvable Mars Campaign

- Internal NASA and other Government
- International Partners
- Commercial and Industrial
- Academic
- Technology developments
- Science discoveries



- Establish capacity for people to live and work in space indefinitely
- Expand human presence into the solar system and to the surface of Mars





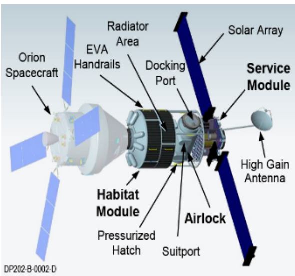
- An ongoing series of architectural trade analyses, guided by Strategic Principles, to define the capabilities and elements needed for a sustainable human presence on Mars
- Builds off of previous studies and ongoing assessments
- Provides clear linkage of current investments (SLS, Orion, etc.) to future capability needs

	EMC Focus Question	Current Areas of Study	Status
A	**How do we pioneer an extended human presence on Mars that is Earth independent?**	• Reusable, long-life, refurbishable and refuelable elements • Build-up scenarios for ISRU to reduce logistics chain and increase sustainability	• Refining habitat and transportation stage concepts • Evaluating campaign w/ ISRU fueled in-space transportation system • Assessing water-rich Mars architecture impacts
B	**What are the objectives, engineering, and operational considerations that drive Mars surface landing sites?**	• Mars exploration and science objectives for increasing durations • Landing Site Requirements and Constraints	• Evaluating sites proposed from Oct 2015 EZ workshop • Assessing mass estimates for surface tunnel and power cabling • Evaluating surface power trades
C	**What sequence(s) of missions do we think can meet our goals and constraints?**	• Campaign concepts that satisfy the strategic principles	• Assessing more minimalist approach and campaign impacts • Assessing later dates for crewed Mars orbit missions
D	**Is a reusable Mars transportation system viable?**	• Repurposing of ARV capabilities • Reuse of habitat, propulsion stages - 1100 day habitat refurbishment and reusable SEP for multiple missions	• Assessing refueling, refurbishment, and recertification in cislunar of habitat and SEP • Commercial launch of propellants implication on SLS launch rate
E	**Can ARV derived SEP support Mars cargo delivery requirements?**	• Evolved ARV to transport cargo and optionally crew to Mars vicinity and return safely (41mt roundtrip with crew)	• Performing SEP propulsion system refinement and assessing system consistency with evolved ARV capabilities
F	**How can we maximize commonality across Mars ascent, Mars vicinity taxi, exploration vehicle and initial deep-space habitation component?**	• Minimal common MAV be used for Mars Taxi, Mars Moon Exploration vehicle, & surface rover? • Trade study of propulsion system (LOx/ CH4 and Hypergols)	• Defining smallest credible MAV cabin and assessing commonality across the architecture • Assessing whether a fueled ascent stage can be landed in combination with an orbital taxi/boost stage
G	**What are the required capability investments for the EMC over the next five years?**	• Capability development prior to sending crew to Mars vicinity • Capabilities and FTOs for ISS testing • Capabilities and FTOs for cislunar testing	• Defining Proving Ground satisfaction criteria • Refining SMT capability roadmaps • Quantifying development efforts and required ISS and cislunar testing

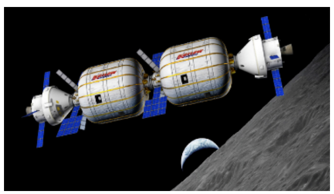
	EMC Focus Question	Current Areas of Study	Status
H	**What is the appropriate habitation system?**	• Assess 1,100-day habitat that is less than 41mt with logistics/spares for crew of 4 • Identify evolvability and of functional requirements of Mars hab system	• NextSTEP BAA • Assessing various initial cislunar habitation concepts (commercial, international, internal)
I	**Is Phobos a viable human target?**	• Explore via teleops from orbit and addition of a short duration excursion mission • Options for sample acquisition and handling	• Precursor SKG identification • Developing data-driven functional requirements and ops concepts for robotic tasks as a function of comm latency • Assessing extra mass capability beyond what is needed for a taxi
J	**What are potential Mars surface pathfinder concepts?**	• With SMD and OCT, identify potential orbital and lander pathfinder concepts	• Integrating performance assessments and conops for 3 Mars EDL concepts • Assessing viability of solar power for Mars ISRU demo if needed • Trade single pathfinder mission to Mars vs multiple Earth based tests
K	**What capabilities are needed to enable elements to survive long dormancy periods in space?**	• Cislunar aggregation concepts and Mars system pre-deploy missions with associated dormancy periods	• Assessing Phobos hab and lander integration with transportation system in cislunar • Evaluating capability of the hab propulsion system to sustain until aggregation • Evaluating pre-deploy dormancy needs
L	**What communications capabilities are needed?**	• Comm needs for Proving Ground and Mars Vicinity	• Assessing other architecture elements (SEP bus) to provide comm and station keeping • Communications deployment strategy
M	**Can humans safely perform 1100 day missions in deep space?**	• Risk mitigation systems and operational approaches to keep crew safe for Mars vicinity missions	• Using data from 1 year ISS mission • Proposed additional long duration Mars analog missions on ISS
N	**Can there be synergy between landers for multiple planetary surfaces?**	• Surface exploration with 5mt, 8mt or 20mt lander • EDL system for 20mt lander	• Evaluating various lander sizing concepts including crew cabin configurations; crews with minimal canopy; hypergols vs methane; refueling and ISRU; descent issues; impacts to campaign risk

NextSTEP Habitation Studies

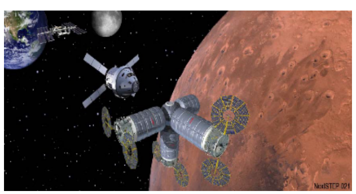
NASA awarded four Phase 1 industry-led studies to develop concepts for a cis-lunar habitat.



- **Lockheed Martin:** Habitat to augment Orion's capabilities. Design will draw strongly on LM and partner Thales Alenia's heritage designs in habitation and propulsion.



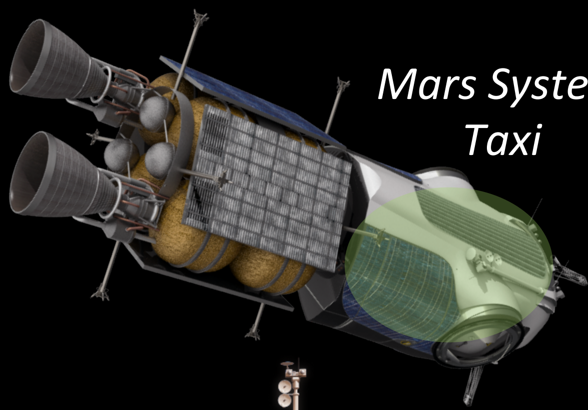
- **Bigelow Aerospace:** The B330 for deep-space habitation will support operations/missions in LEO, DRO, and beyond cis-lunar space



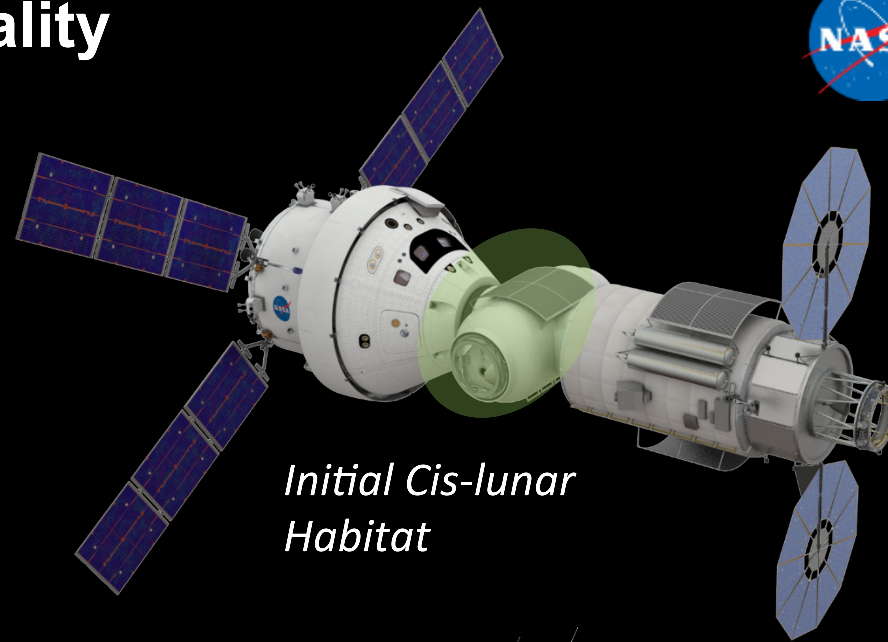
- **Orbital ATK:** Habitat that employs a modular, building block approach that leverages the Cygnus spacecraft to expand cis-lunar and long duration deep space transit habitation capabilities and technologies.

- **Boeing:** Developing a simple, low cost Exploration Augmentation Module (EAM) that is affordable early on, that allows various technologies to be tested over time, and that is capable of evolving into a long-duration crew support system for cis-lunar and Mars exploration.

EMC Small Habitat Commonality

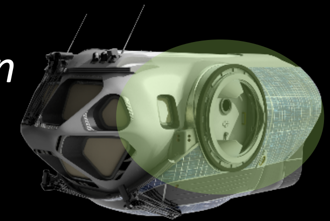


Mars System Taxi

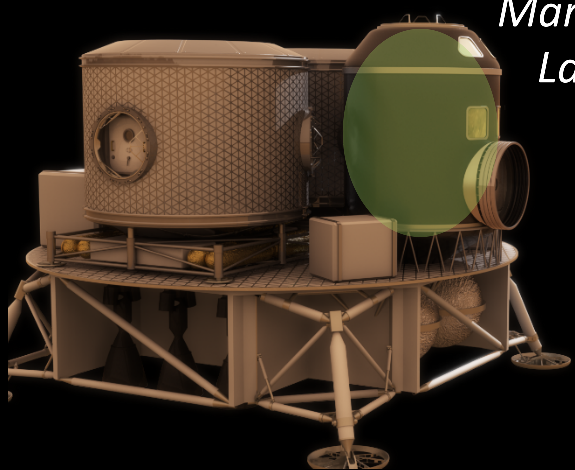


Initial Cis-lunar Habitat

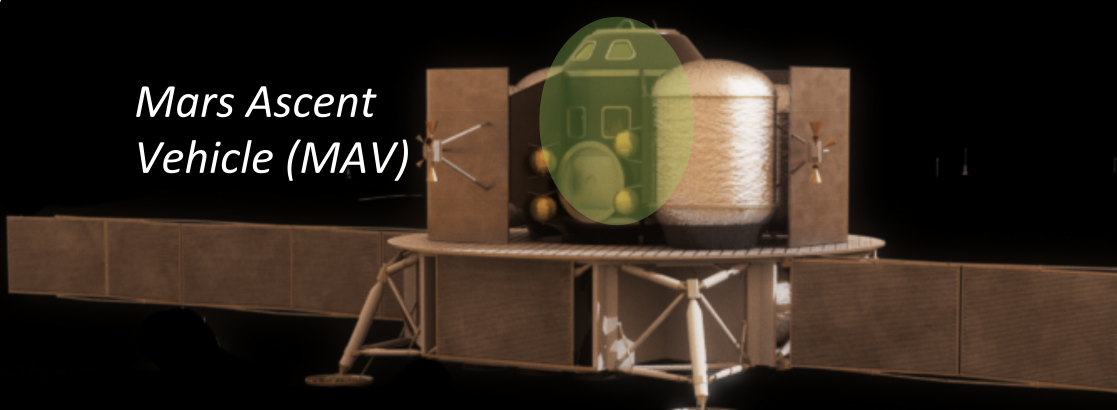
Mars Surface Rover



Phobos Exploration Vehicle (PEV)



Mars Crew Lander



Mars Ascent Vehicle (MAV)

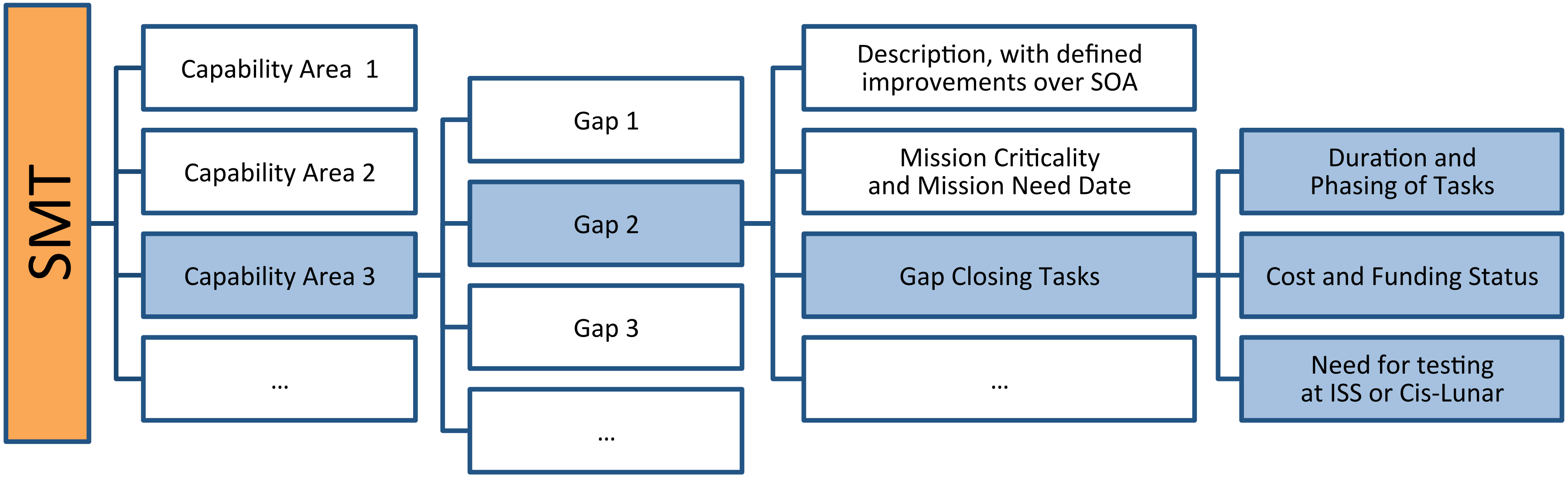
System Maturation Teams - Integrated capability investment decisions with traceability to human exploration needs

System Maturation Team
Autonomous Mission Operations (AMO)
Communication and Navigation (Comm/Nav)
Crew Health & Protection and Radiation (CHP)
Environmental Control and Life Support Systems and Environmental Monitoring (ECLSS-EM)
Entry, Descent and Landing (EDL)
Extra-vehicle Activity (EVA)
Fire Safety
Human-Robotic Mission Operations
In-Situ Resource Utilization (ISRU)
Power and Energy Storage
Propulsion
Thermal (including cryo)
Discipline Team - Crosscutting
Avionics
Structures, Mechanisms, Materials and Processes (SMMP)

- The SMTs comprise subject matter experts from across the agency who have been involved in maturing systems and advancing technology readiness for NASA. They are:
  - Defining performance parameters and goals for each of the 14 capabilities
  - Developing maturation plans and roadmaps for the identified performance gaps
  - Specifying the interfaces between the various capabilities
  - Ensuring that the capabilities mature and integrate to enable future pioneering missions.
- The subject matter experts that compose each SMT are responsible for understanding their capabilities across all missions and elements within the Evolvable Mars Campaign.
- The SMTs work closely with the Evolvable Mars Campaign to coordinate capability needs & gaps.
- STMD's Principal Technologists are members of the SMTs and coordinate the STMD investment planning with identified capability needs and gaps.

System Maturation Team Data Hierarchy

- **System Maturation Teams (e.g. Propulsion) – divided into Capability Areas**
  - **Capability Areas** (e.g. High Thrust Propulsion) – divided into Gaps
    - **Gap** (e.g. Pump-Fed LOX/CH4 In-Space Engine) – defines a capability advancement over the current state of the art along with mission criticality and mission need date; gap is closed by performing multiple Gap Closing Tasks
      - **Gap Closing Tasks** (e.g. Power Pack Development) – defines task duration and phasing, cost and funding status, and development testing locations (ISS or cis-lunar)



Transportation of Crew and Cargo To/From Deep Space

Challenges

Deliver crew and cargo to deep space

Return crew from deep space

Space Launch System

Transport crew and cargo to cis-lunar space

- ✓ Initial launch vehicle that can launch 36 t to TLI
- ✓ Upgraded launch vehicle that can launch 43 t to TLI
- ✓ Option for 5, 8.4, or 10 m diameter shroud
- ✓ 1/year launch rate with surge to 2/year for cis-lunar missions
- ✓ 2/year launch rate with surge to 3/year for Mars missions

Orion

Support crew during trip to/from cis-lunar space

- ✓ 4 crew for 21 days
- ✓ Contingency EVA in a Launch, Entry, and Abort (LEA) suit using umbilical life support
- ✓ Ability to rendezvous and dock with other in-space elements
- ✓ Deep space navigation
- ✓ Earth entry from cis-lunar space: 11 km/s

Commercial Launch

Use commercial launch vehicles to deliver logistics and small cargo to cis-lunar space

- ✓ Small cargo vehicle to deliver up to 11 t to TLI
- ✓ Shroud = 5 m diameter

In-Space Transportation

Mars EDL

Deliver crew and cargo to Mars surface

- ✓Possible aerocapture at 6.3 km/s if not propulsively delivered to orbit
- ✓Entry velocity of 3.8 – 4.7 km/s
- ✓100 m precision landing with hazard avoidance
- ✓Supersonic retropropulsion with LOX/CH_4 engine
- ✓Deployable/Inflatable (16-23 m) entry systems
- ✓Surface access at +2 km MOLA
- ✓20-30 t payload to the surface, 40-60 t arrival at Mars

Challenges

- Transport crew and cargo to/from Mars vicinity
- Provide access to Mars surface
- Provide transportation within the Mars system
- Uncrewed operations during deployment and between uses

Common Capabilities

Chemical Propulsion

Common LOX/CH_4 Pump-Fed Engine:

- ✓ Thrust: 25 klbf
- ✓ Isp: 355-360 s
- ✓ Up to 15 year lifetime
- ✓ 150-500 s burn time
- ✓ 5:1 throttling
- ✓ Near-ZBO storage with 90 K cryocooler

LOX/CH_4 Pressure-Fed RCS:

- ✓ Thrust: 100-1000 lbf; Isp: 320 s

Electric Propulsion

Deliver approx. 40-60 t to Mars orbit

200-kW class solar array system (BOL at 1 AU) using 30% efficient GaAs, triple junction solar cells

300 V array system converted to 800 V for EP and 28 V for spacecraft

ARRM-Derived Hall Thruster:

- ✓ Common Xe storage and feed system with 13.3 kW thruster
- ✓ Isp: 2000 s or 3000 s modes

SEP - Hybrid

Combined SEP and hypergolic propulsion system delivers crew and cargo to Mars vicinity

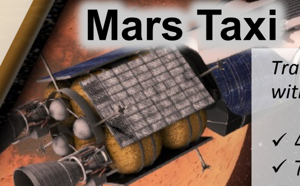
- ✓ 2 x 200-kW class arrays
- ✓ 1,100 days total trip mission time, 300 days at Mars
- ✓ >16 kW thermal rejection
- ✓ Ability to refuel 24 t of Xe on orbit
- ✓ 15 year lifetime, 3 uses, 3 refuelings

Mars Ascent

Return crew and cargo from Mars surface

- ✓ 4 crew and 250 kg payload from ±30 deg latitude, 0 km MOLA to Mars parking orbit
- ✓ 26 t prop (20 t O_2, 6 t CH_4), 35 t total liftoff mass, 8 t Earth launch dry mass
- ✓ Up to 3 days flight duration
- ✓ 5 years dormant before use
- ✓ Use of ISRU-produced oxygen

Mars Taxi



Transport crew and cargo within the Mars system

- ✓ 4 crew for up to 2.5 days
- ✓ 7 t inert mass, 14 t wet mass
- ✓ 8 kW EOL at Mars solar power
- ✓ Reusable and refuelable

SEP - Chemical

SEP delivers cargo to Mars vicinity, and LOX/CH_4 propulsion delivers crew to/from Mars vicinity

- ✓ 1 x 200-kW class solar array
- ✓ >8 kW thermal rejection
- ✓ Flight times to Mars approx. 1,400 days
- ✓ 4-6 years dormant before use

Living in Space: Long Duration Habitation

Challenges

Protect and support crew in deep space for up to 1100 days

Uncrewed operations during deployment and between uses

Reduced logistics and spares

Earth - independent operations

Common Capabilities

4 Crew for 500-1100 days

Common pressure vessel

15 year lifetime with long dormancy periods

Design for reusability across multiple missions

100 m^3 habitable volume and dry mass < 22 t

Autonomous vehicle health monitoring and repair

Advanced Exploration ECLSS with >85% H_2O recovery and >75% O_2 recovery from reduced CO_2

ECLSS System (w/o spares): <5 t mass, <9 m^2 volume, <4 kW power

Environmental monitoring with >80% detection rate without sample return

14-kW peak operational power and thermal management required

Autonomous mission operations with up to 24 minute one-way time delay

Autonomous medical care, behavioral health countermeasures, and other physiological countermeasures to counteract long duration missions without crew abort

Exercise equipment under 500 kg

Provide 20-40 g/cm^2 of radiation protection

EVA pressure garment and PLSS <200 kg

Contingency EVA operations with 1 x 2-person EVA per month

Communications to/from Earth and between elements

Mars Surface Habitat

Live and operate on the Mars surface in 1/3 g

- ✓ 4 crew for up to approx. 500 days
- ✓ 48 m^3 volume for logistics and spares
- ✓ Logistics Mass: 10.7 t
- ✓ 4 years dormant before use
- ✓ 3-4 years dormant between uses
- ✓ EVA system with surface mobility, dust mitigation, and atmospheric compatibility

Phobos Habitat

Live and operate in microgravity at Phobos

- ✓ 4 crew for up to approx. 500 days
- ✓ 48 m^3 volume for logistics and spares
- ✓ Logistics Mass: 10.7 t
- ✓ EVA system with Phobos mobility and dust mitigation
- ✓ 4-5 years dormant before use
- ✓ 3 years dormant between uses

Transit Habitat

Live and operate in microgravity during trip to/from Mars

- ✓ 4 crew for up to 1,100 days
- ✓ 93 m^3 volume for logistics and spares
- ✓ Logistics Mass: 21 t
- ✓ 4 years dormant before use and between uses

Living in Space: Short Duration Habitation

Excursion Vehicle

Explore kilometers away from the destination habitat

- ✓ 2 crew for up to 2 weeks, contingency 4 crew for 1 week
- ✓ EVA pressure garment and PLSS <200 kg with dual-band radio avionics and radiation hardened bio-med sensors
- ✓ High frequency EVA (15 min. ingress-egress time)
- ✓ 4 years dormant before first use and between uses
- ✓ Design for reuse for 3 missions
- ✓ Lightweight exercise equipment under 25 kg

Challenges

Protect and support crew in deep space for up to 60 days

Uncrewed operations during deployment and between uses

Earth - independent operations

Initial Cis - Lunar Habitation

Support crew each year for short duration stays in cis-lunar space

- ✓ 4 crew for up to 60 days
- ✓ EVA pressure garment and PLSS <200 kg with dual-band radio avionics and rad-hardened bio-med sensors
- ✓ High frequency EVA (15 min. ingress-egress time)
- ✓ Lightweight exercise equipment under 25 kg
- ✓ 1 year dormant before use
- ✓ Up to 300 days dormant between uses

Common Capabilities

4 crew for short durations (up to 60 days)

Support autonomous mission operations with time delay

Common, partially closed ECLSS under approx. 800 kg (3 years MTBF and 2 crew per torr of CO_2 removal)

Autonomous rendezvous, prox ops, and docking

Ability to be teleoperated with <0.5 s latency

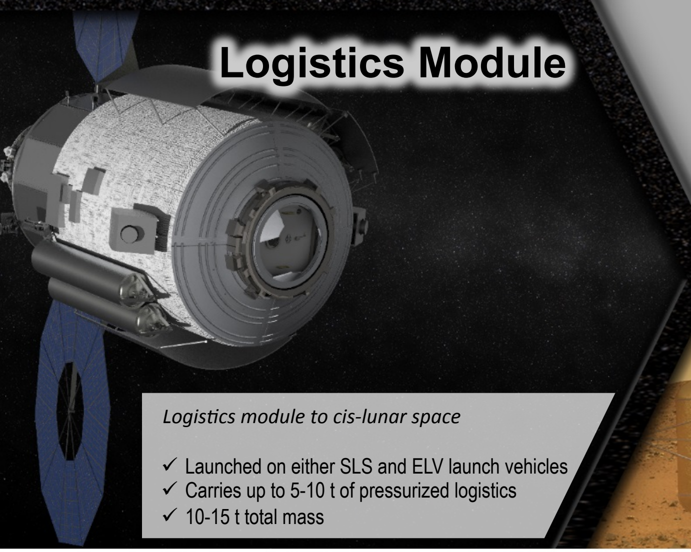
Communications to/from Earth and between elements

Common, lightweight pressure vessel and common hatch

15 year lifetime with long dormancy periods

Design for maintainability

Logistics Module



Logistics module to cis-lunar space

- ✓ Launched on either SLS and ELV launch vehicles
- ✓ Carries up to 5-10 t of pressurized logistics
- ✓ 10-15 t total mass

Mars Ascent Vehicle

Return crew to Mars orbit

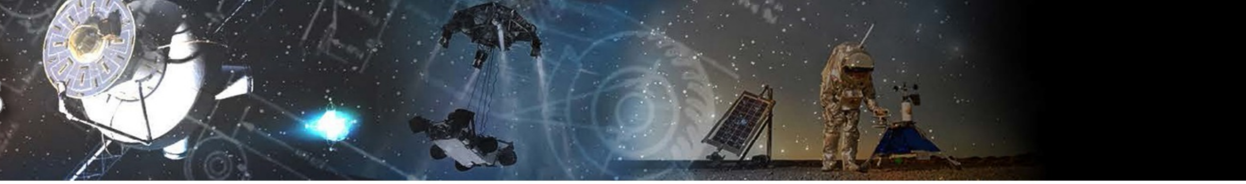
- ✓ 4 crew for up to 3 days flight duration
- ✓ Open loop ECLSS under approx. 400 kg
- ✓ 5 years dormant before use

Mars Taxi

Transport crew between Mars orbit and Mars Moons

- ✓ 4 crew for up to 2.5 day crewed duration
- ✓ 560 days operational (uncrewed) at Mars
- ✓ 2 years dormant before use
- ✓ Up to 1.5 years dormant between uses

Destination Systems



Challenges

Uncrewed operations during deployment and between uses

Extracting and processing local resources

Operations in harsh environments

Phobos / Deimos

- ✓ Mobility power generation of 1-3 kW BOL and 120 kW-hr eclipse storage
- ✓ Mobility systems for crew (2 nominal, 4 contingency) and cargo (up to 3 t) with approx. 40 km range
- ✓ RCS mobility sled for excursion vehicle
- ✓ Dormant for 6 years at Phobos/Deimos before use
- ✓ Dormant for 3 years between uses
- ✓ All elements have 15 year lifetime
- ✓ Low-g body docking and interaction

Mars Surface

- ✓ 40 kW stationary Mars surface power
- ✓ 1-5 kW deployable/mobile Mars power
- ✓ Mars surface rover for crew (2 nominal, 4 contingency) and cargo (up to 3 t) with a range of 90 km per charge and max speed of 10 km/hr
- ✓ Mars surface ISRU plant capable of processing >2.2 kg/hr of atmosphere CO_2 into O_2 with a process efficiency of 36%, power of 20-22 kWe, and is less than 1 t
- ✓ Liquification and cryogenic fluid storage in Mars atmosphere
- ✓ All systems dormant for 4-5 years before first use and between uses
- ✓ All elements have 15 year lifetime
- ✓ Offloading and transport systems capable of up to 10 t

Common Capabilities

Ability to prospect for usable resources (e.g. water, oxygen, carbon, nitrogen) to achieve Earth-independence

Ability to be teleoperated from other destination elements

Support autonomous mission operations with time delay

Communications to/from Earth and between elements

Robotic support for setup, operations, and maintenance

Sample acquisition

Dust mitigation

Cis - Lunar/Asteroid

- ✓ Acquisition and processing of 0.08 – 1.6 kg/day of water, oxygen, and/or hydrocarbons at 10 – 20 % efficiency
- ✓ Low-g body grappling/capture and manipulation
- ✓ Hub for exploration vehicle aggregation and servicing

Moon

- ✓ Robotic rover with acquisition and processing of icy regolith

HEOMD/STMD Engagement on Technology Needs

- **Evolvable Mars Campaign (EMC) has a strategic set of needs for enabling long-range capabilities; Orion and SLS needs are primarily near-term and mission focused.**
- **Crosscutting needs identified by HEOMD:**
  - Radiation monitoring & protection (ISS, Orion, HRP, EMC)
  - EVA suit & PLSS (Orion, ISS, ARM, EMC)
  - Environmental monitoring (Orion, ISS, EMC)
  - Spacecraft fire safety (Orion, ISS, EMC)
  - Exercise equipment (Orion, HRP, EMC)
  - Advanced solar arrays (ARM, ISS, EMC)
  - Automated rendezvous & docking (Orion, ARM, EMC)
- **Areas with greatest number of gaps:**
  - Human Health, Life Support, & Habitation Systems (Orion, HRP)
  - Communications & Navigation (SCAN)
- **Categories of collaboration:**
  - **Deliveries:** STMD matures technology and delivers to AES for system-level evaluation (e.g advanced space suit components.)
  - **Partnerships:** STMD and HEOMD/AES co-fund the development of technologies that are of mutual interest (e.g. Mars 2020 payloads.)
  - **Coordination:** STMD and HEOMD/AES define specific divisions of responsibility within a technical discipline (e.g. synthetic biology, advanced manufacturing, etc.)

Capability Development Risk Reduction

= Sufficiently Funded
= Partially Funded

	Capability \ Mission	ISS	Cis-lunar Short Stay (e.g. ARM)	Cis-lunar Long Stay	Cis-Mars Robotic	Mars Orbit	Mars Surface
Working in Space and On Mars	In Situ Resource Utilization & Surface Power		Exploratory ISRU Regolith	Exploratory ISRU	Exploratory ISRU & Atmosphere	Exploratory ISRU	Operational ISRU & High Power
	Habitation & Mobility	Long Duration with Resupply	Initial Short Duration	Initial Long Duration		Resource Site Survey	Long Duration / Range
	Human/Robotic & Autonomous Ops	System Testing	Crew-tended	Earth Supervised	Earth Monitored	Autonomous Rendezvous & Dock	Earth Monitored
	Exploration EVA	System Testing	Limited Duration	Full Duration	Full Duration	Full Duration	Frequent EVA
Staying Healthy	Crew Health	Long Duration	Short Duration	Long Duration	Dust Toxicity	Long Duration	Long Duration
	Environmental Control & Life Support	Long Duration	Short Duration	Long Duration		Long Duration	Long Duration
	Radiation Safety	Increased Understanding	Forecasting	Forecasting Shelter	Forecasting Shelter	Forecasting Shelter	Forecasting & Surface Enhanced
Transportation	Ascent from Planetary Surfaces				Sub-Scale MAV	Sub-Scale MAV	Human Scale MAV
	Entry, Descent & Landing				Sub-Scale/Aero Capture	Sub-Scale/Aero Capture	Human Scale EDL
	In-space Power & Prop		Low power	Low Power	Medium Power	Medium Power	High Power
	Beyond LEO: SLS & Orion		Initial Capability	Initial Capability	Full Capability	Full Capability	Full Capability
	Commercial Cargo & Crew	Cargo/Crew	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity
	Communication & Navigation	RF	RF & Initial Optical	Optical	Deep Space Optical	Deep Space Optical	Deep Space Optical
		EARTH RELIANT	PROVING GROUND			EARTH INDEPENDENT	

Mars Exploration Capability Summary Assessment

Capabilities	Assessment
In Situ Resource Utilization & Surface Power	Resource Prospector and MOXIE are small-scale demonstrations of ISRU on planetary bodies. These would need to be significantly scaled up to support human exploration needs.
Habitation & Mobility	ISS is demonstrating long-duration habitation in LEO, but duration depends on resupply. Conceptual studies are underway for short duration cis-lunar habitats.
Human/Robotic & Autonomous Ops	Human/Robotic & Autonomous Ops are being demonstrated on ISS. Substantial additional work is needed to enable maintenance of human exploration systems.
Exploration EVA	Uncertain if next generation spacesuit will be ready before 2024 for demonstration on ISS.
Crew Health	Human Research Program is investigating crew health risks on ISS, and developing medical diagnostics and countermeasures. Some health risks may not be controlled by 2024.
Environmental Control & Life Support	ISS life support systems require frequent maintenance. New ECLSS technologies are being demonstrated on ISS. Long-duration, closed-loop, system-level ECLSS demonstration is being planned.
Radiation Safety	Characterizing LEO, cis-lunar, and Mars surface radiation environments. Improving forecast models for solar particle events. Reducing uncertainty in radiation effects on humans. Effective shielding has not been developed.
Ascent from Planetary Surfaces	Little work is being done in this area except for MAV concept studies and small LOX-methane propulsion efforts.
Entry, Descent & Landing	There are multiple EDL technology development activities for Mars robotic missions but analogous projects for human missions are in early stages of progress.
In-space Power & Propulsion	Developing 40 kW SEP system for ARM. Initiating ground testing of 100 kW electric thrusters. Developing small fission reactors for surface power (low funding level).
Beyond LEO: SLS & Orion	Proceeding toward first flight of SLS and Orion in 2018.
Commercial Cargo & Crew	Proceeding toward Commercial Crew IOC in 2018. Opportunities for resupply of cis-lunar habitats.
Communication & Navigation	Demonstrating high bandwidth optical communications for cis-lunar and Mars. Deep space optical comm is a candidate for demonstration on SMD missions.

Summary

- The Journey to Mars requires a resilient architecture that can embrace new technologies, new international / commercial partners, and identify agency investment choices to be made in the near, mid and long term.
- The Evolvable Mars Campaign:
  - Informs the agency choices by providing technical information from a cross agency, end-to-end integrated analysis
  - Needs to continue to develop linkages to the agency decision making and capability investment processes
- Regardless of which path is ultimately selected, there is a set of common capabilities required to be developed by NASA and its partners over the next 10 years